Global/Hadron physics at PHENIX

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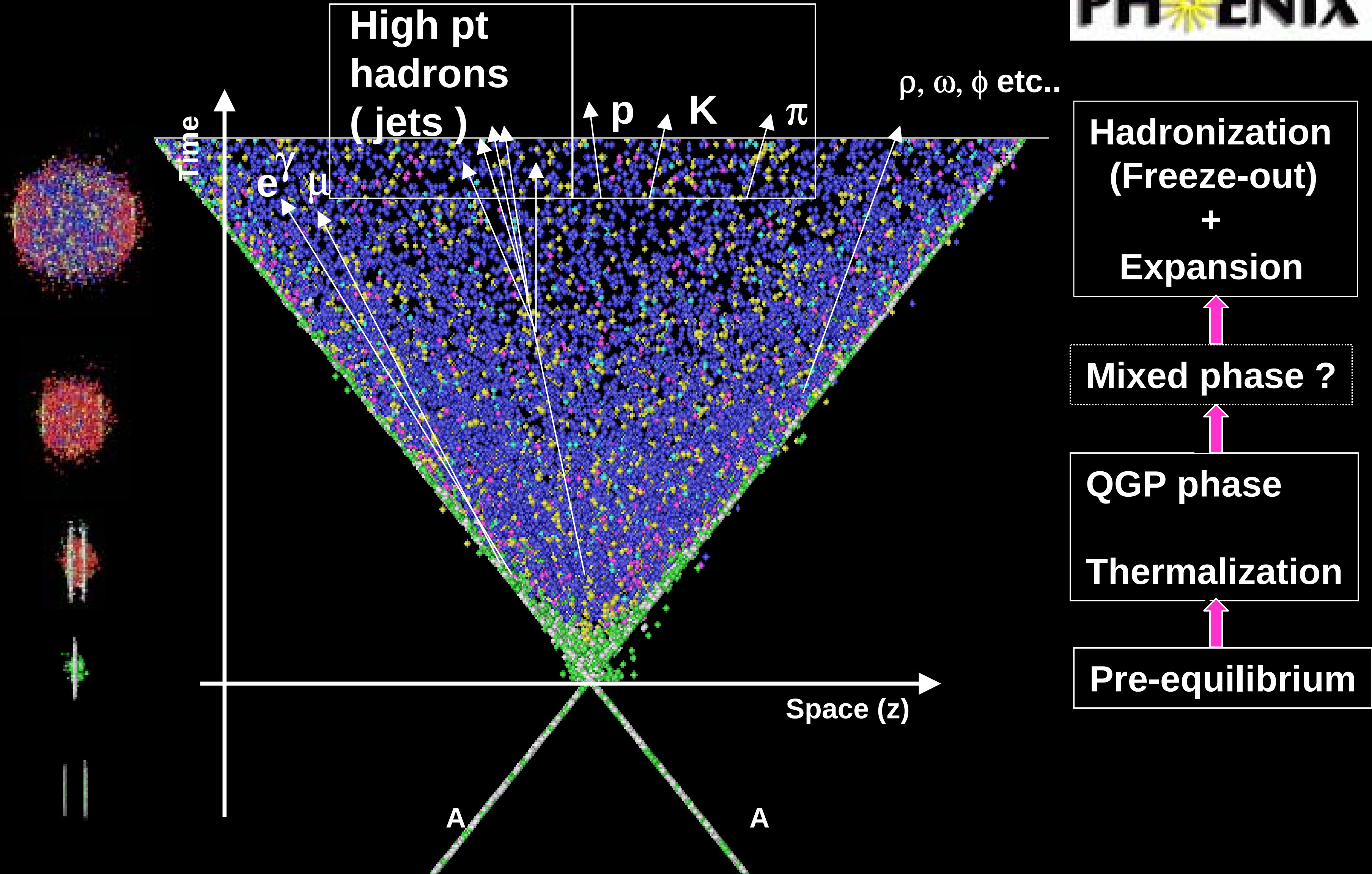
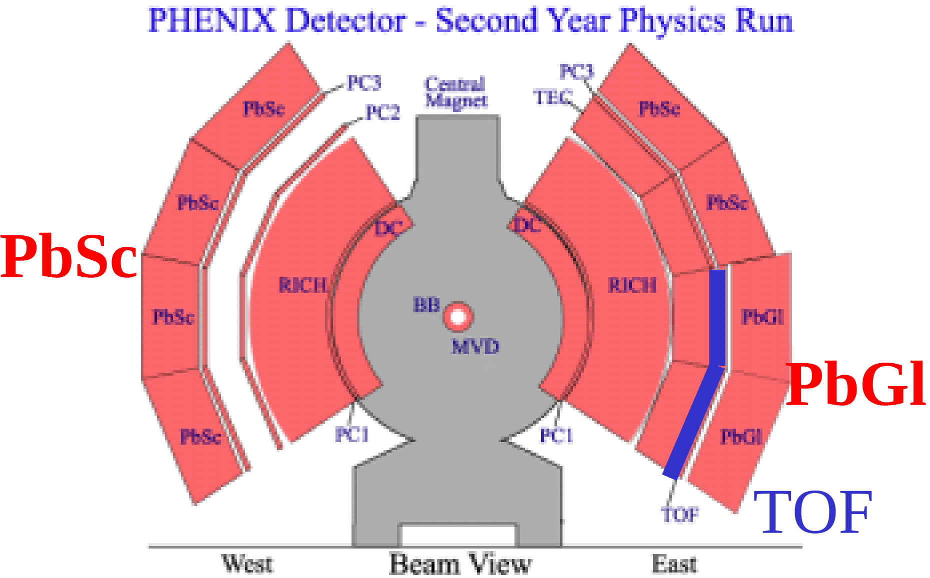
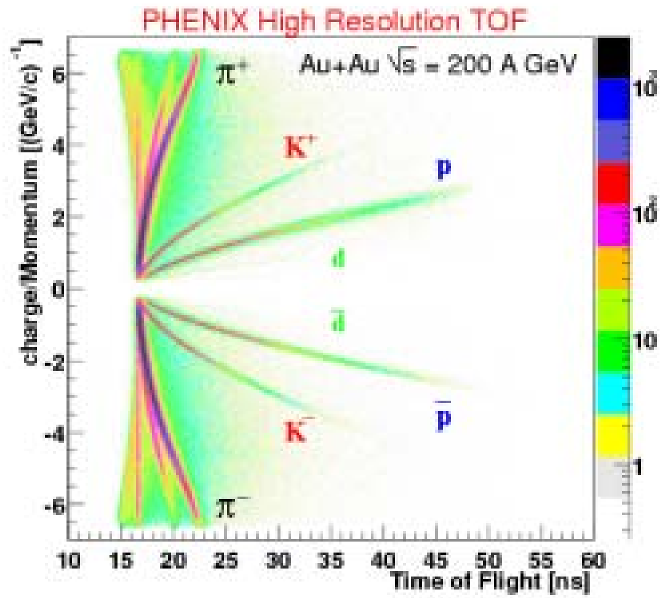
Space-time Evolution of A+A collision



Hadrons reflect the bulk property of collision system and its evolution.
High p_T hadrons carry information at the early stage of the evolution.

PHENIX Central Arm



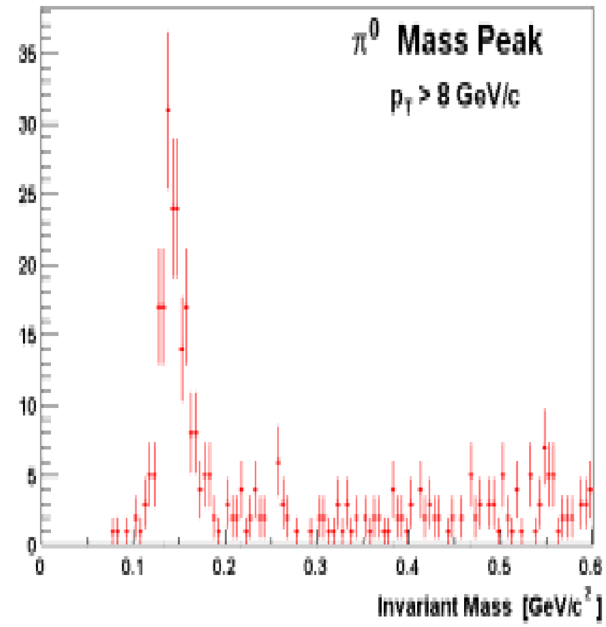


PID by high resolution TOF

- π, K < 2 GeV/c
- proton, anti-proton < 4 GeV/c
- $\Delta\phi = \pi/4$

π0 measurement by EMCal

- 1<pt<10GeV/c
- 6 lead- scintillator (PbSc) sectors
- 2 lead- glass (PbGl) sectors
- $|\eta|<0.38$ at midrapidity, $\Delta\phi = \pi$



Focus of this talk

How the collision system evolves?

- Initial energy density (Nch and E_T)
- Collective expansion ($<p_T>$, Single particle spectra)
- How the system freeze-out? (HBT puzzle)

What happens at the early stage?

- Indication of early thermalization (Elliptic flow)
- Quark/gluon propagation in the dense medium
  - Evidence for jets in Au+Au collisions
  - Suppression of high p_T hadrons
  - Baryon/meson ratio in high p_T range

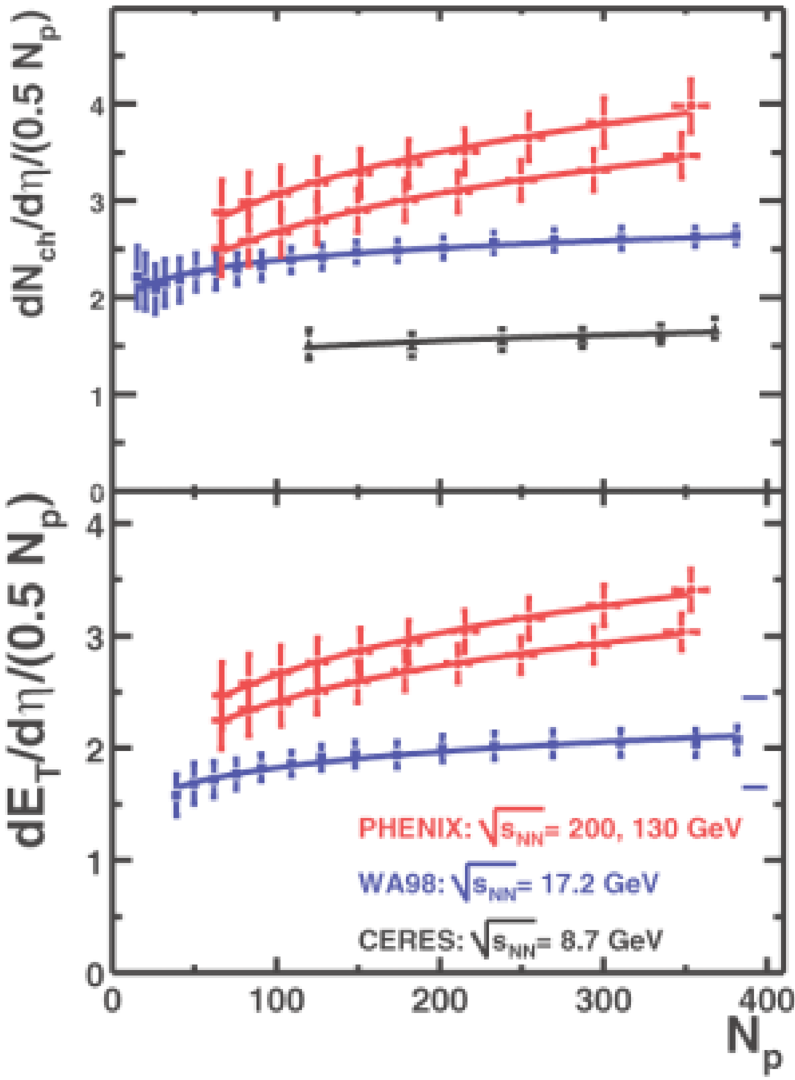
Initial energy density

- Charged particle multiplicity and transverse energy significantly higher at RHIC compared to SPS.
- N_{ch} and E_T per participant pair increases w.r.t. participants (centrality).

  Large contributions from binary collisions (hard scattering).
- Energy density in 2% most central collisions

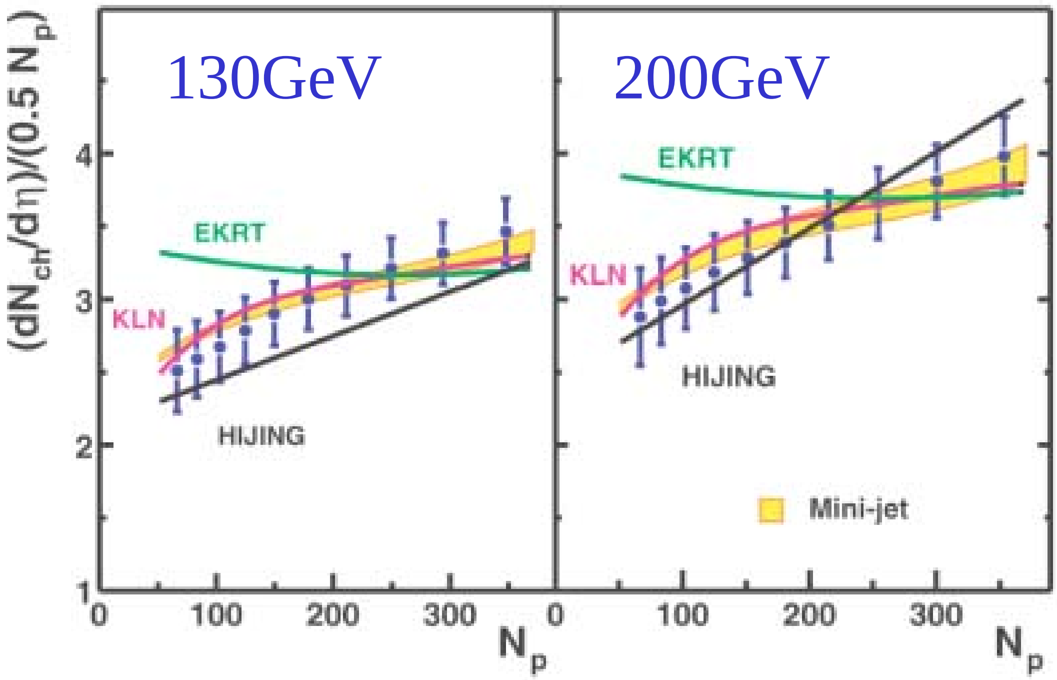
$$\varepsilon = \frac{1}{\pi R^2 \tau_0} \cdot \frac{dE_T}{d\eta}$$

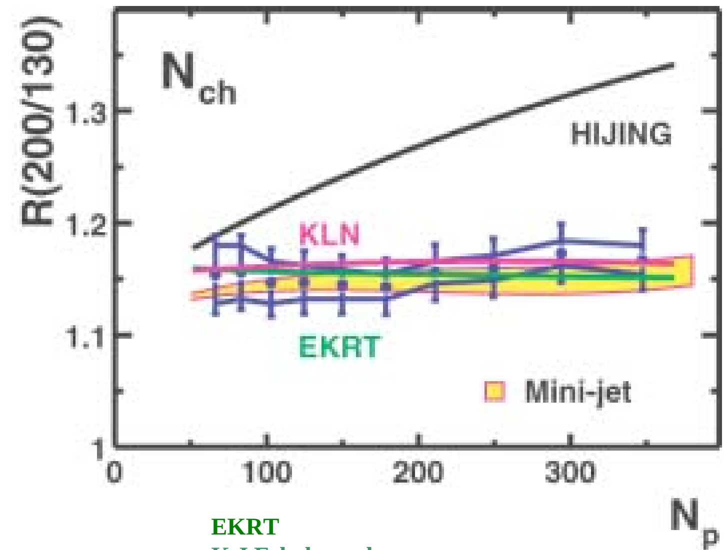
$$\approx 5.5\,\mathrm{GeV/fm^3} \Big/ \left(\frac{\tau_0}{\mathrm{fm}/c}\right) \text{ @ 200GeV}$$



ε is larger than $\varepsilon_{critial}$~1GeV

Model comparison



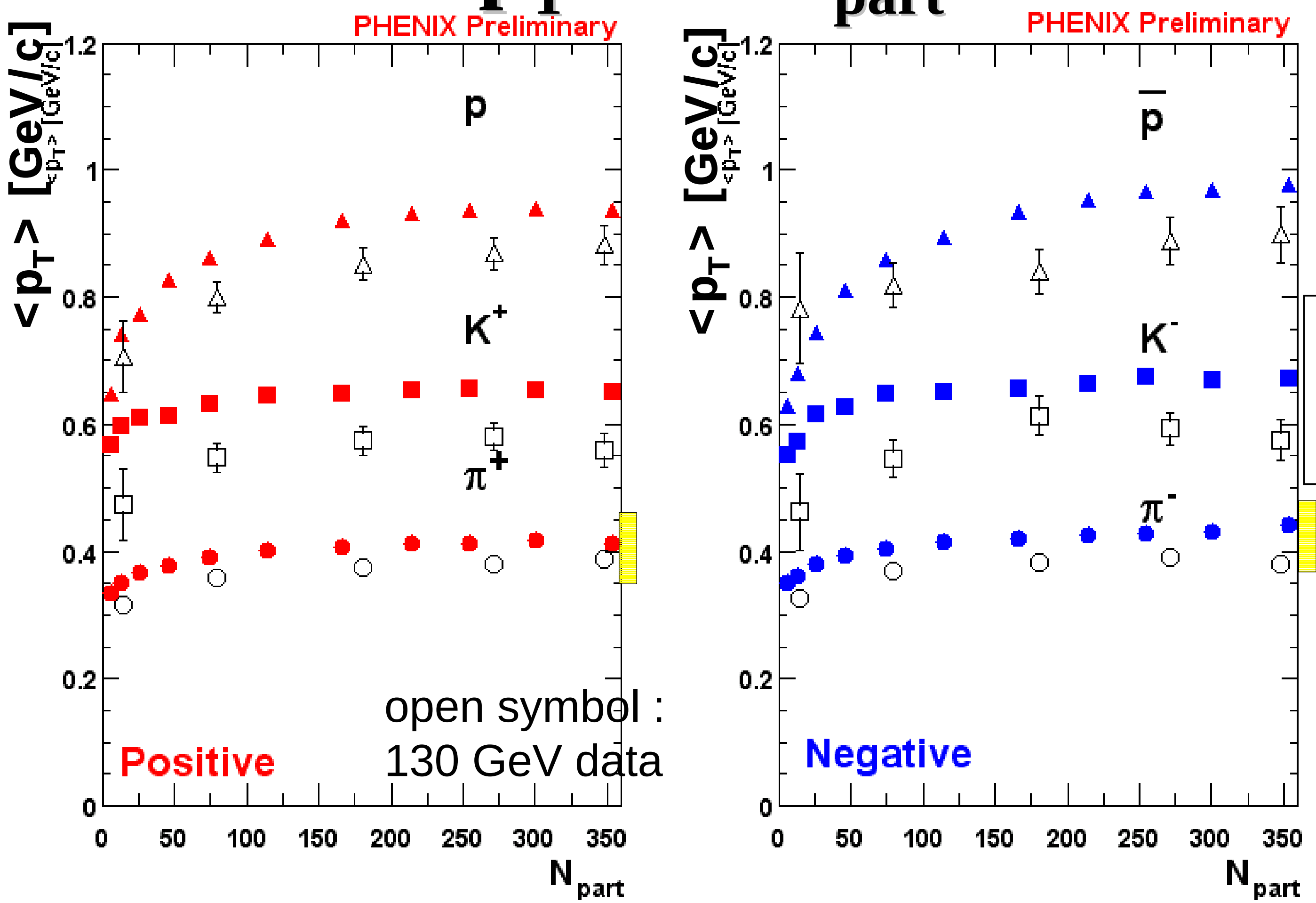


EKRT
K.J.Eskola et al,
Nucl Phys. B570, 379 and
Phys.Lett. B 497, 39 (2001)
HIJING
X.N.Wang and M.Gyulassy,
PRL 86, 3498 (2001)
KLN
D.Kharzeev and M. Nardi, Phys.Lett. B503, 121 (2001)
D.Kharzeev and E.Levin,
Phys.Lett. B523, 79 (2001)
Mini-jet
S.Li and X.N.Wang Phys.Lett.B527:85-91 (2002)

Naïve hard&semi-hard two component model (HIJING) is excluded.

High energy QCD gluon saturation model (KLN) and two-component mini-jet model with nuclear shadowing (Mini-jet) are favored.

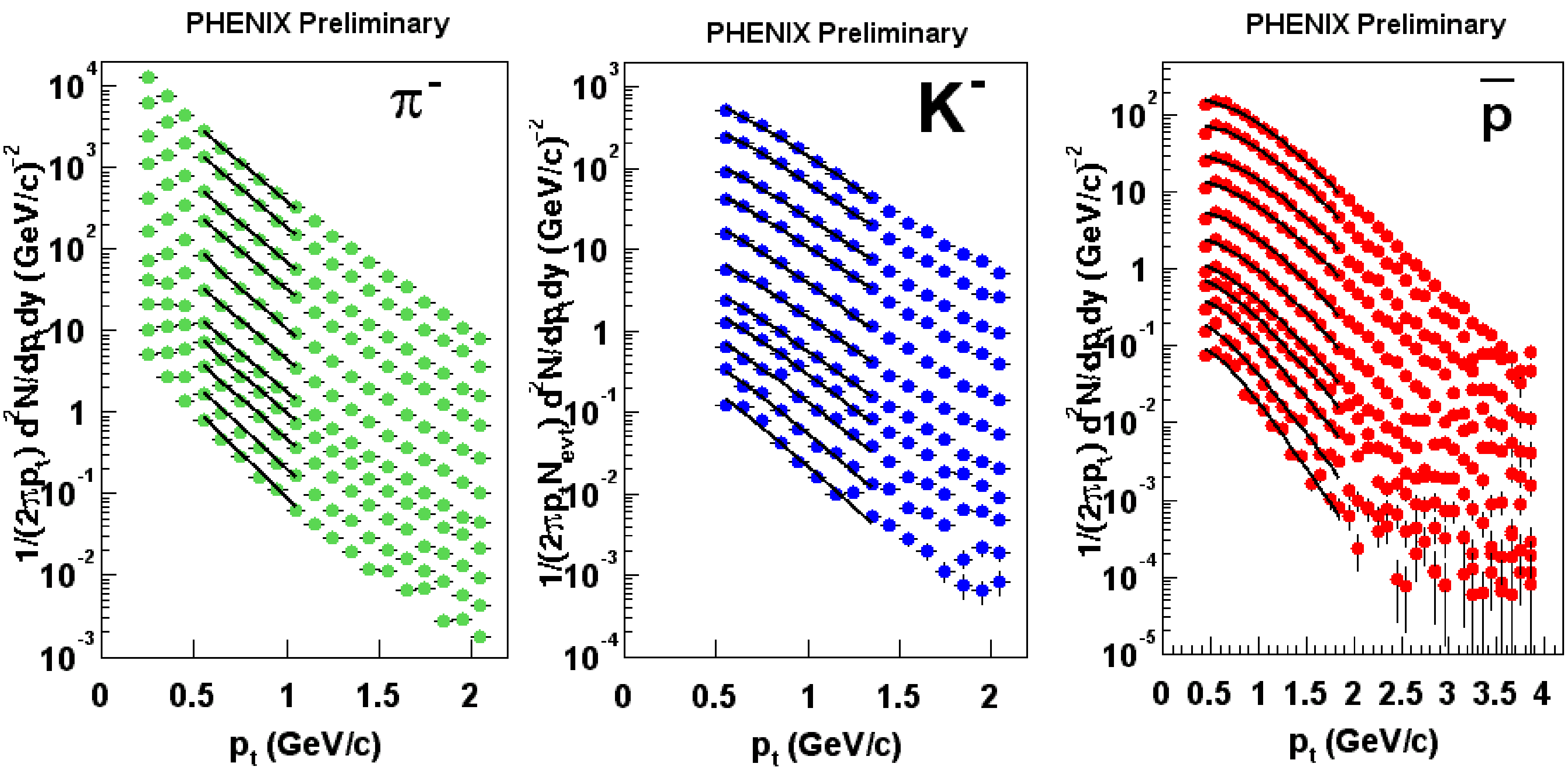
Collective Expansion
- $\langle p_T \rangle$ vs. N_{part} -



•Systematic error on 200 GeV data
π (10 %), K (15 %), p (14 %)

- $\langle p_T \rangle$ increases with N_{part} and particle mass => radial expansion.
- Consistent with hydrodynamic expansion picture.

Collective Expansion
- Single particle p_T spectra -



- Simultaneous fit in range $(m_t - m_0) < 1$ GeV is shown.
- The top 5 centralities are scaled for visual clarity.
- Similar fits for positive particles.

Result of hydrodynamic model fit

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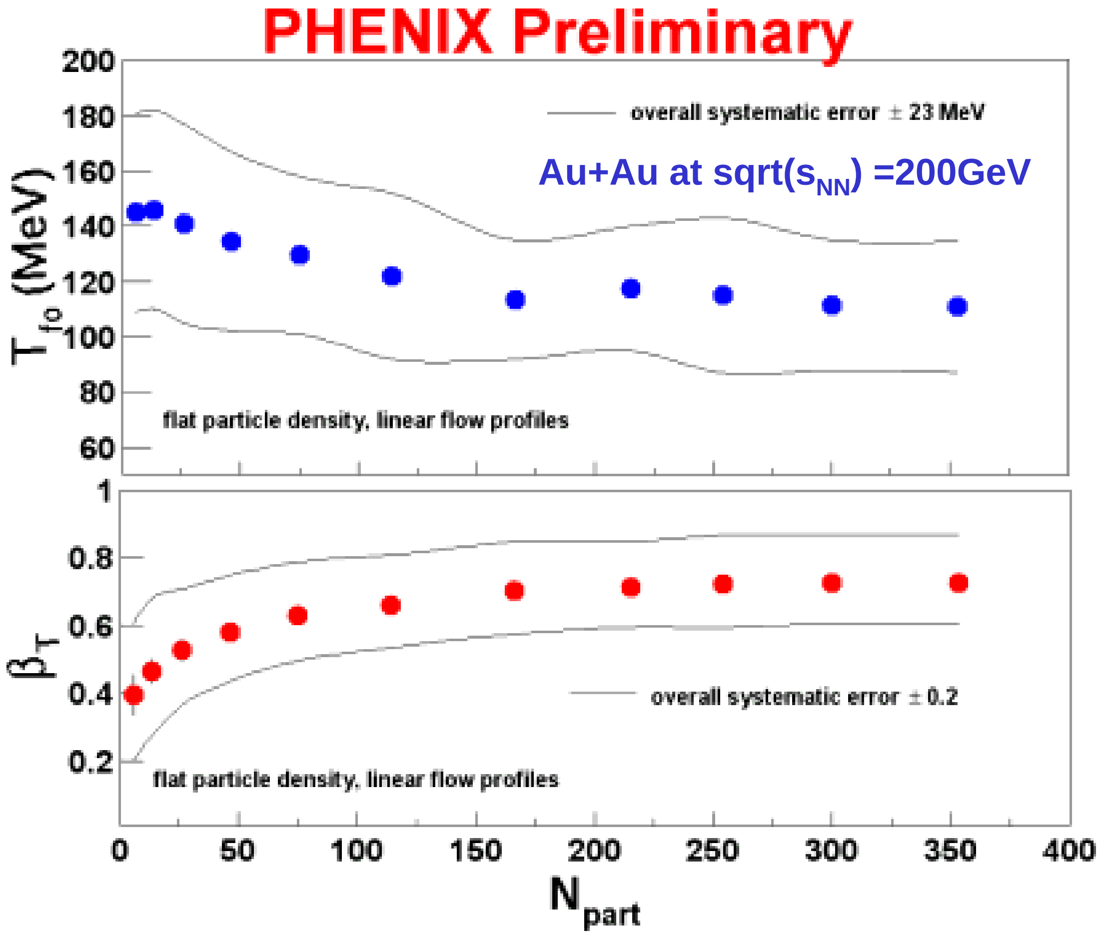

Most central collisions for 200 GeV data

Freeze-out Temperature(*)

$T_{fo} = 110 \pm 23$ MeV

Transverse flow velocity(*)

$\beta_T = 0.7 \pm 0.2$

(*) Resonance feed down is not corrected.

Ref: E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993)

- β_T increases from peripheral to mid-central ($N_{part} < 150$) and tends to saturate for central collisions.

HBT puzzle

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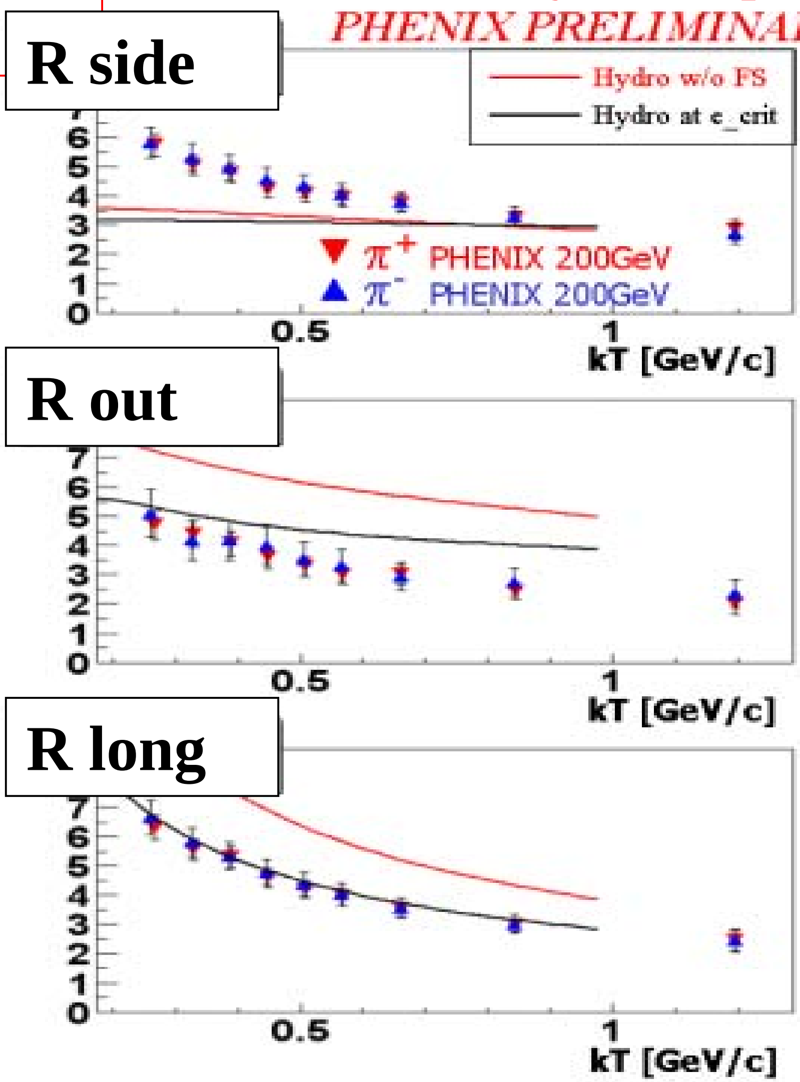
Why duration time $\tau=\text{sqrt}(R_{out}^2-R_{side}^2)/\beta$ of the freeze-out is so short?

Centrality is in top 30%



Hydro w/o Free Streaming

- Standard initialization and freeze out which reproduce single particle spectra.

Hydro at e_{crit}

- Assuming freeze out directly at the hadronization point. ($e_{dec} = e_{crit}$)

kT dependence of R_{long} indicates the early freeze-out?

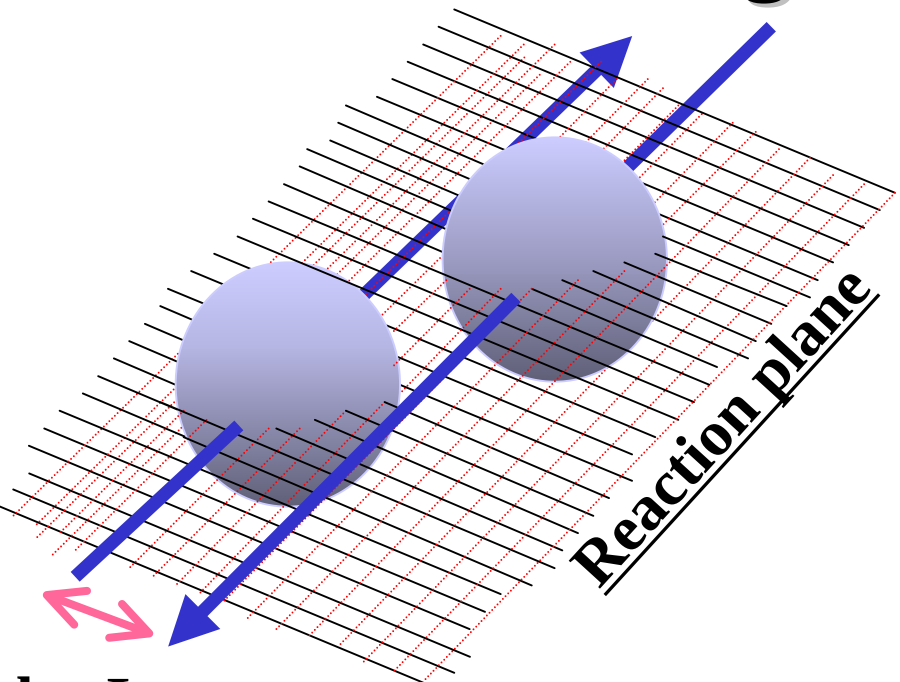
Any initial conditions in hydro. can not solve the small Rside.

Recent hydrodynamic calculation by U.Heinz and P. F. Kolb (hep-ph/0204061)

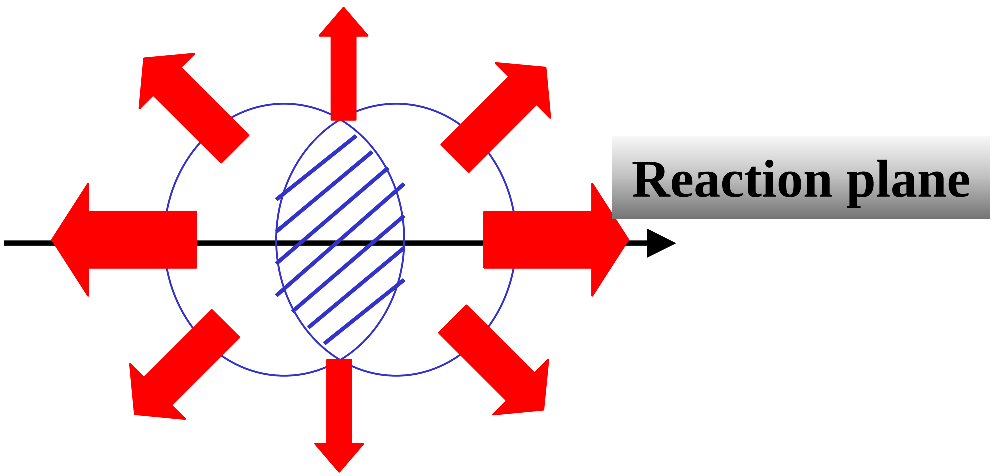
k_T: average momentum of two particles

What happens at the early stage ?

Early thermalization ?
- Strong elliptic flow v_2-



b : Impact parameter



Spatial anisotropy → Momentum anisotropy

$$dN/d\phi = N [\, 1 + \Sigma\, 2 v_n \cos(n\phi) \,]$$

ϕ : azimuthal angle for measured particles from a reaction plane

v_n : anisotropy parameter

v_2 of identified hadrons (π, K, p)

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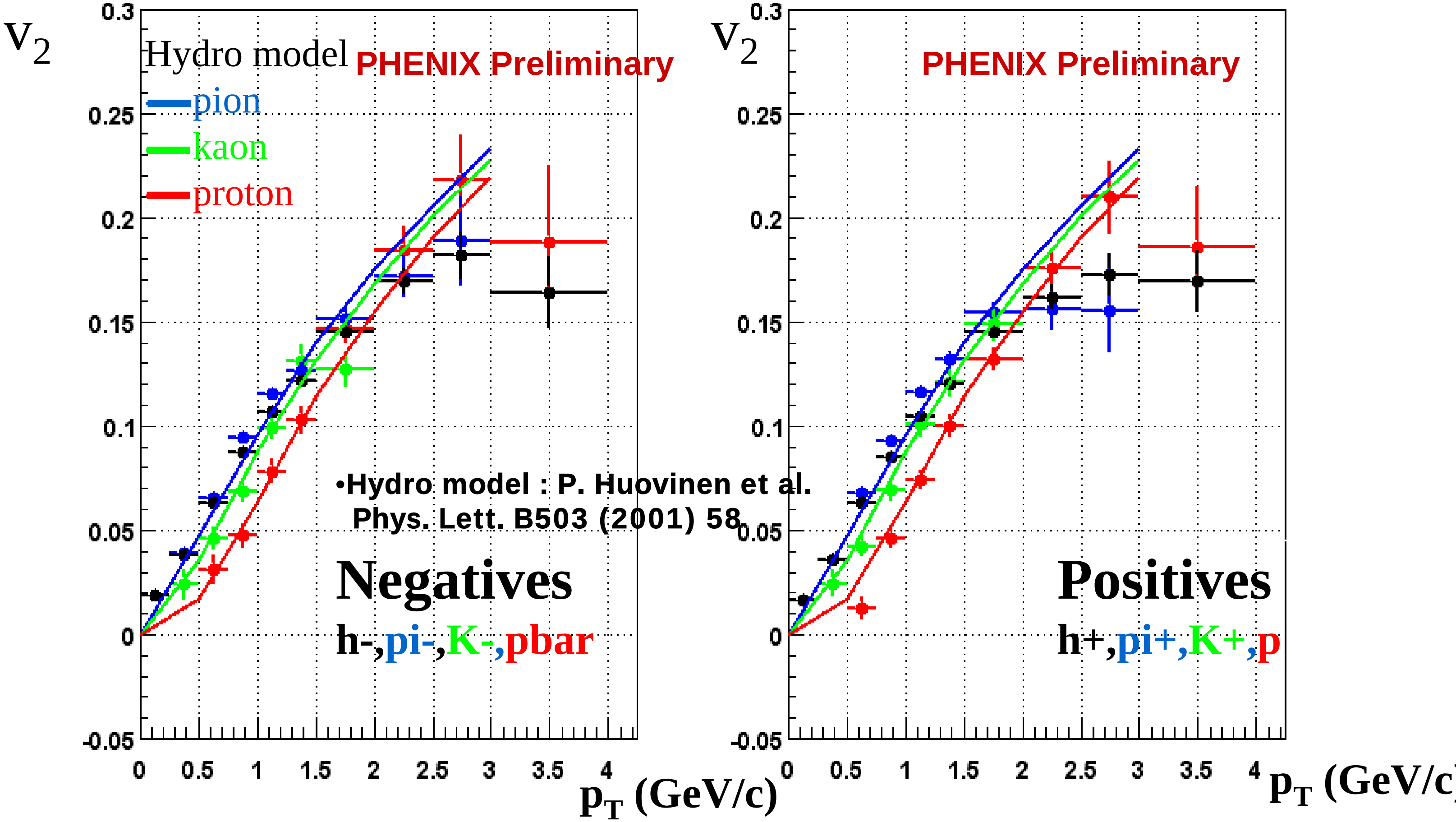
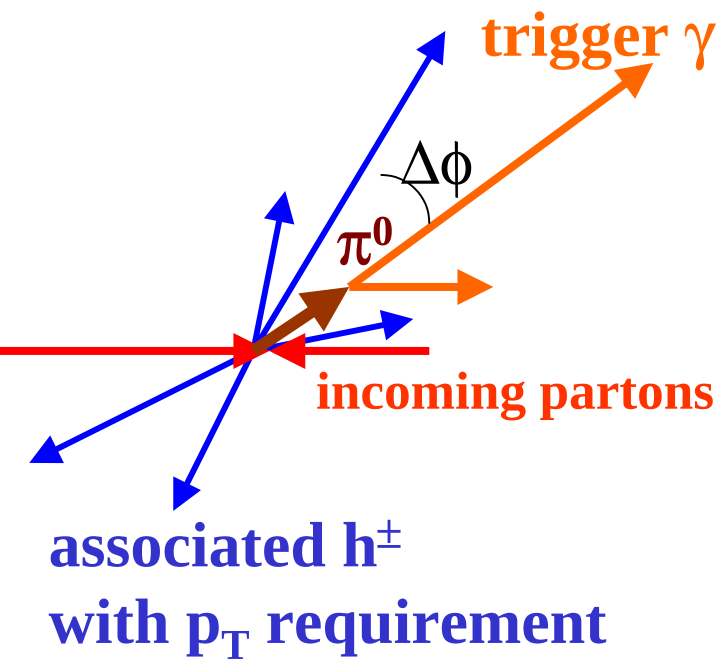
Au+Au at sqrt(s_{NN}) =200GeV, Minimum bias, Reaction Plane | η |=3~4

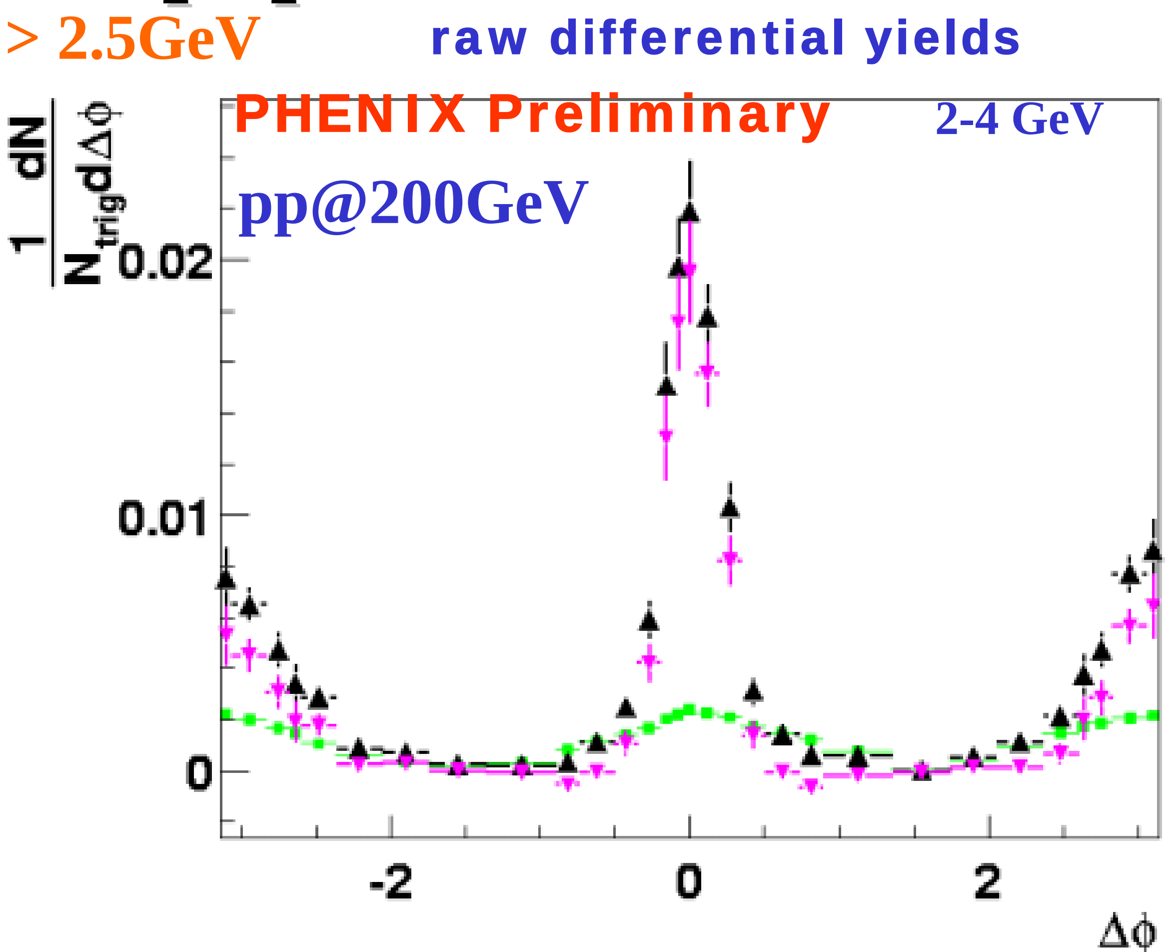


v_2 saturates in p_T > 2GeV/c.

A hydrodynamic model agrees with data in p_T<2GeV/c.

Quark&Gluon in dense medium
- Jets in p+p -

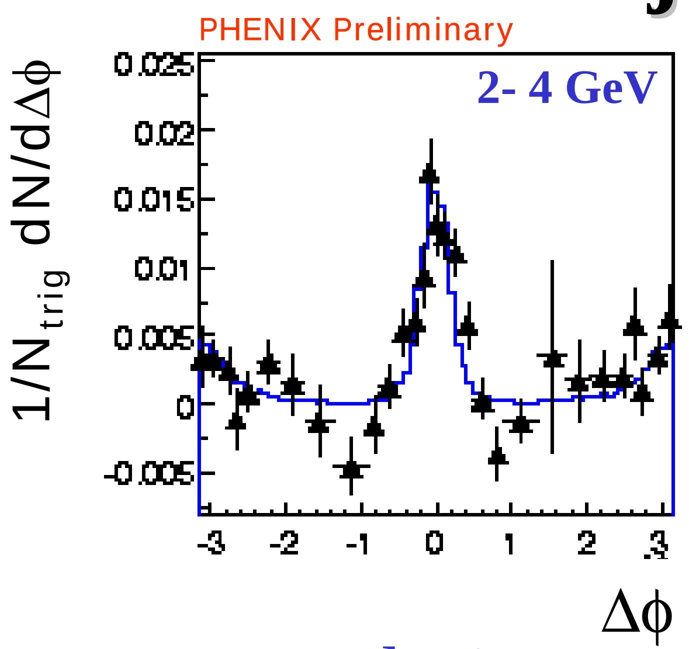


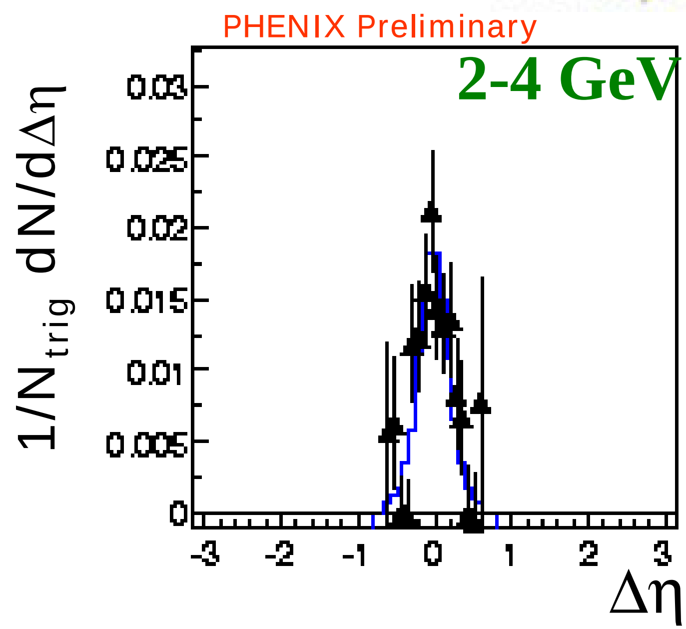


- Jet structure was observed in azimuthal correlation in pp at sqrt(S_{pp})=200GeV.

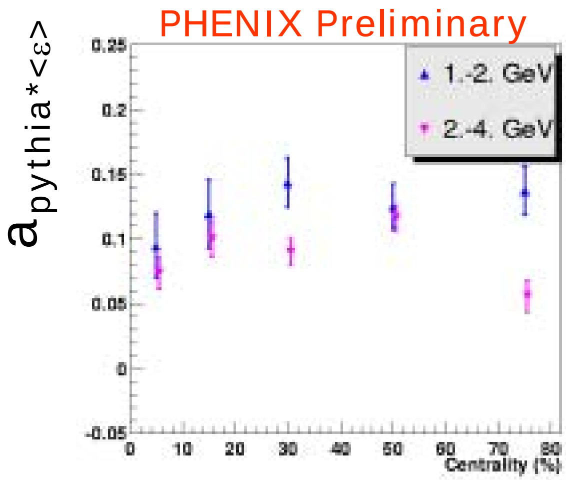
- **black = pair distribution**
- **green = mixed event pair distribution**
- **purple = bkg subtracted distribution**

Evidence for jets in Au+Au



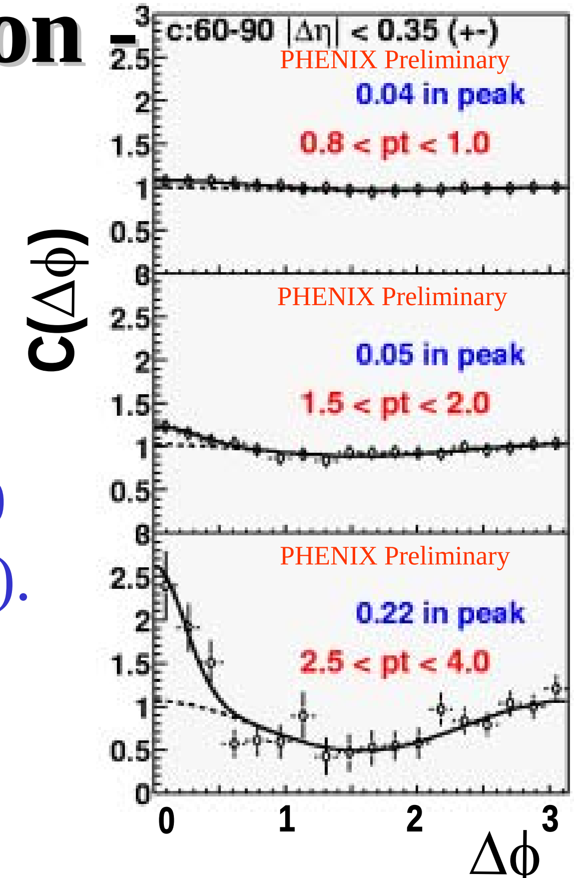


- Use p-p analysis as a reference for Au-Au jet signal
- Correlation seen simultaneously in Δφ and Δη (Jet Cone)

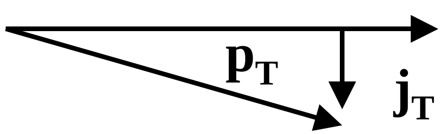


- **In p_T 2-4 GeV/c, Jet-Like Signal dominates over elliptic flow component.**
- **This Jet-Like Signal approx. flat with centrality (no systematic errors yet)**

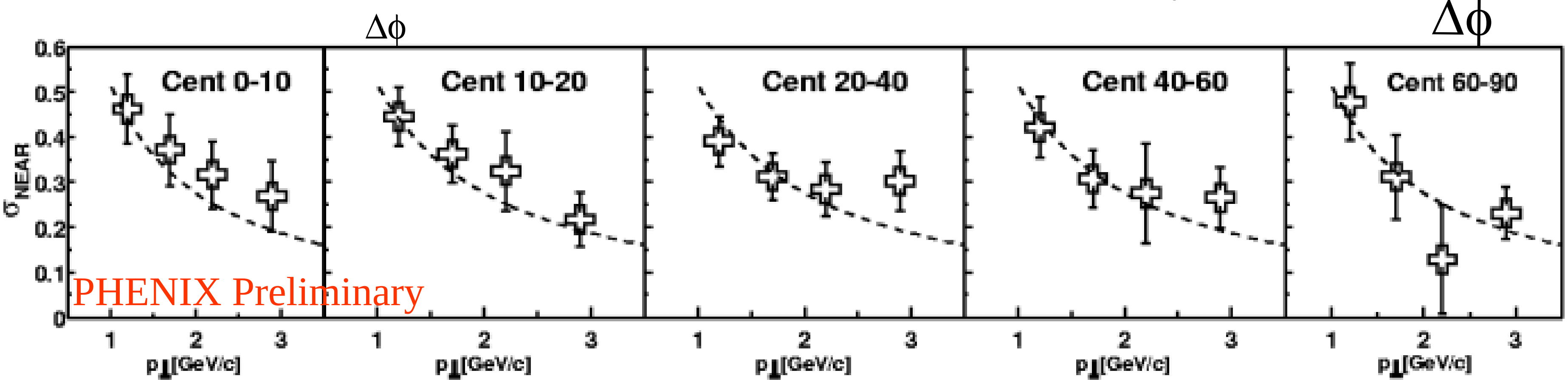
More evidence for jets
- Charged-Charged Correlation -



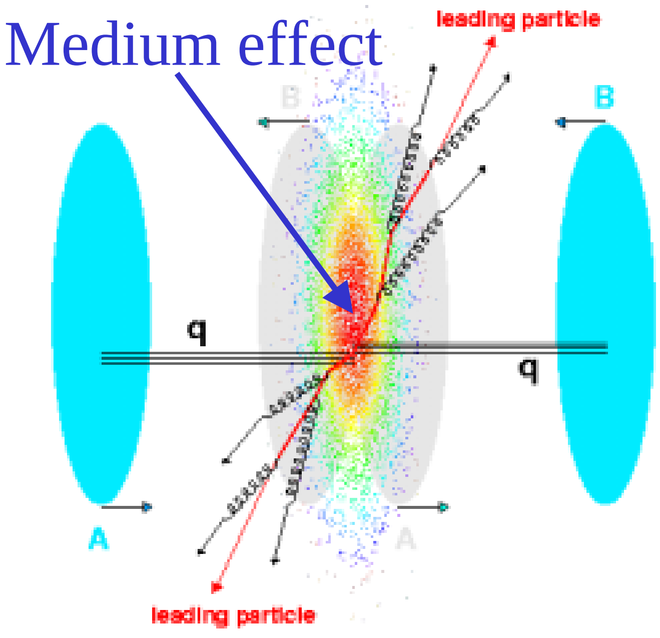
- Correlation fcn for charged hadrons.
- Observe large asymmetry
- Fit to gaussian + cos2φ.
- Width of gaussian peak vs. pt.
- For a jet, the transverse momenta $\langle j_T \rangle \sim 400$ MeV, independent of pt (dashed curve below).



Correlation width $\propto j_T/p_T$

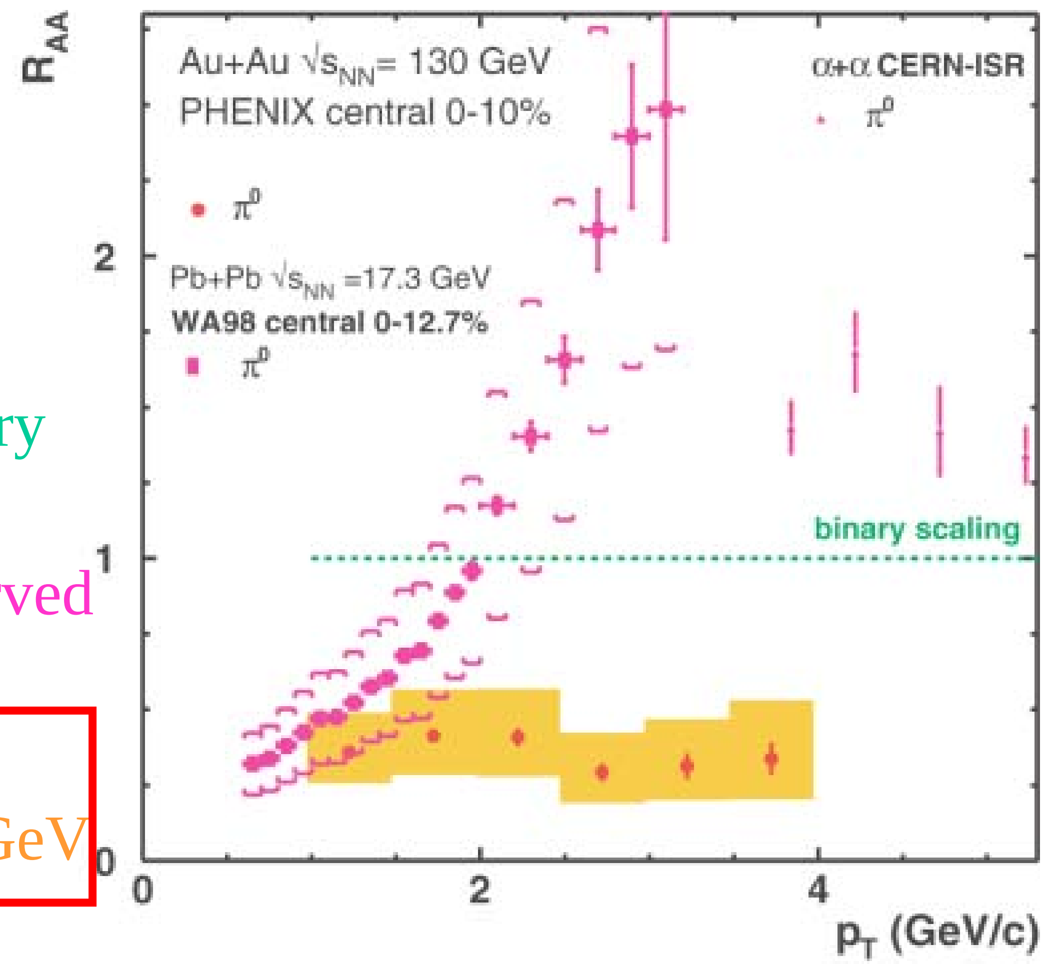


Discovery of high p_T Suppression



Nuclear Modification Factor

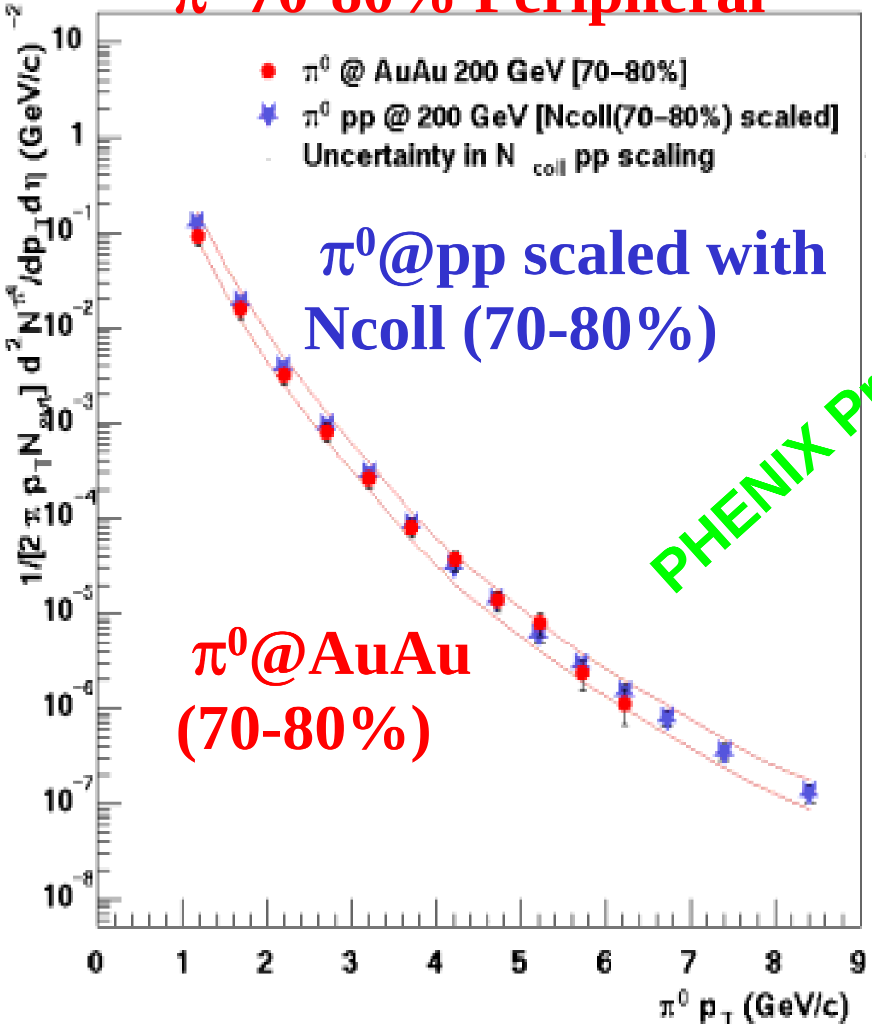
$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_T}{d^2N^{pp}/dydp_T \cdot \langle N_{coll}^{AA} \rangle}$$



- R_{AA} =1 scale with # of binary collisions
- R_{AA} >1 Cronin effect observed in ISR and SPS
- R_{AA} <1 Suppression was discovered in RHIC@130GeV

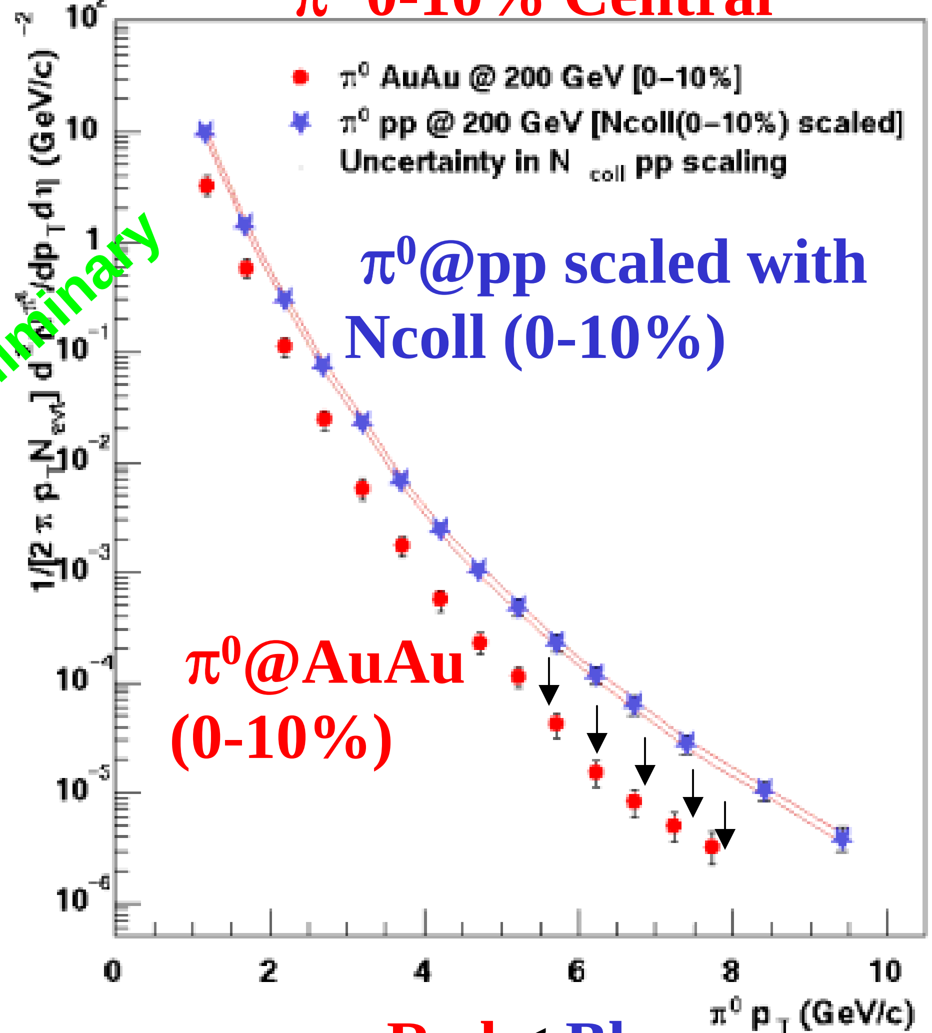
p_T distributions in peripheral & central PHENIX

π^0 70-80% Peripheral



Red = Blue

π^0 0-10% Central

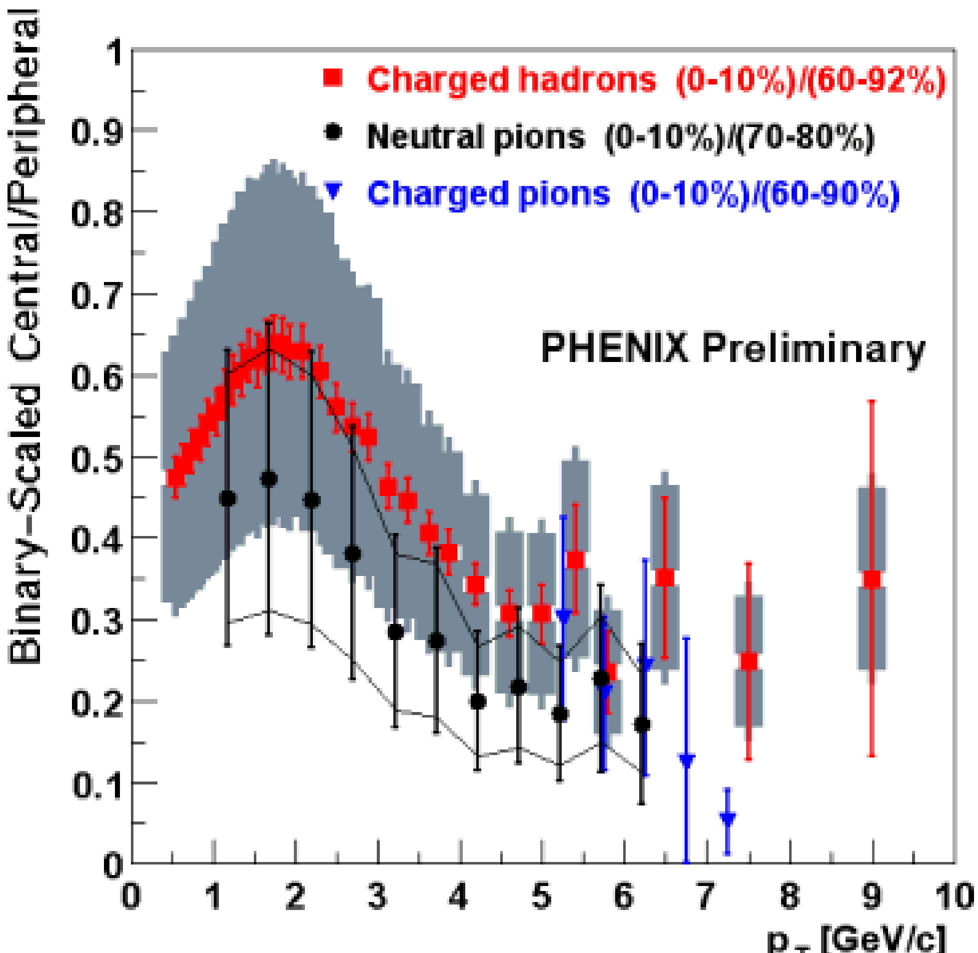


Red < Blue

Strong suppression !!!

Different strength of suppressions

$$\frac{\text{Yield}_{\text{central}} / \langle N_{\text{binary}} \rangle_{\text{central}}}{\text{Yield}_{\text{peripheral}} / \langle N_{\text{binary}} \rangle_{\text{peripheral}}} \approx R_{AA}$$



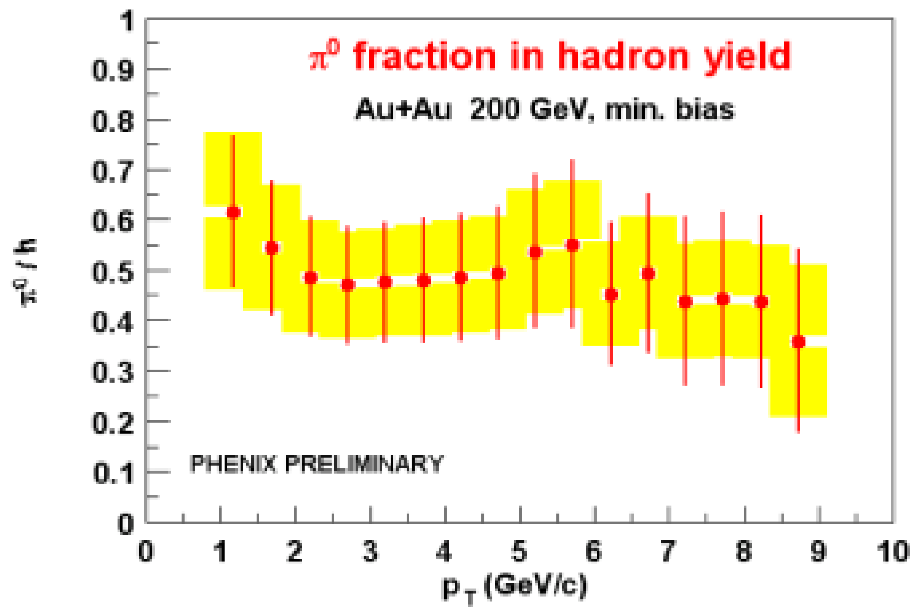
- Different suppressions ?

-- Charged hadrons

-- Charged pions

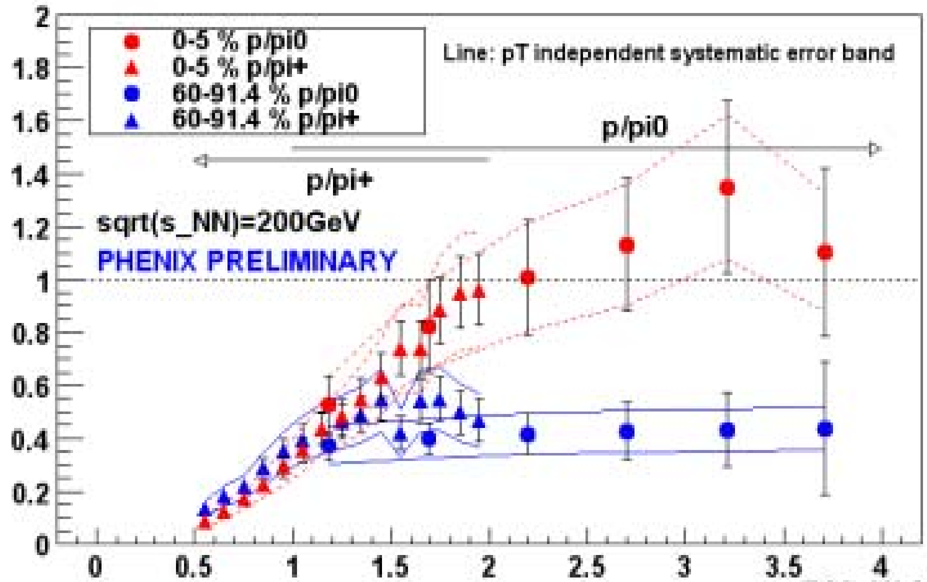
-- Neutral pions

- $\pi^0/(h^+ + h^-)/2$ ratio ~ 0.5 up to 9 GeV/c

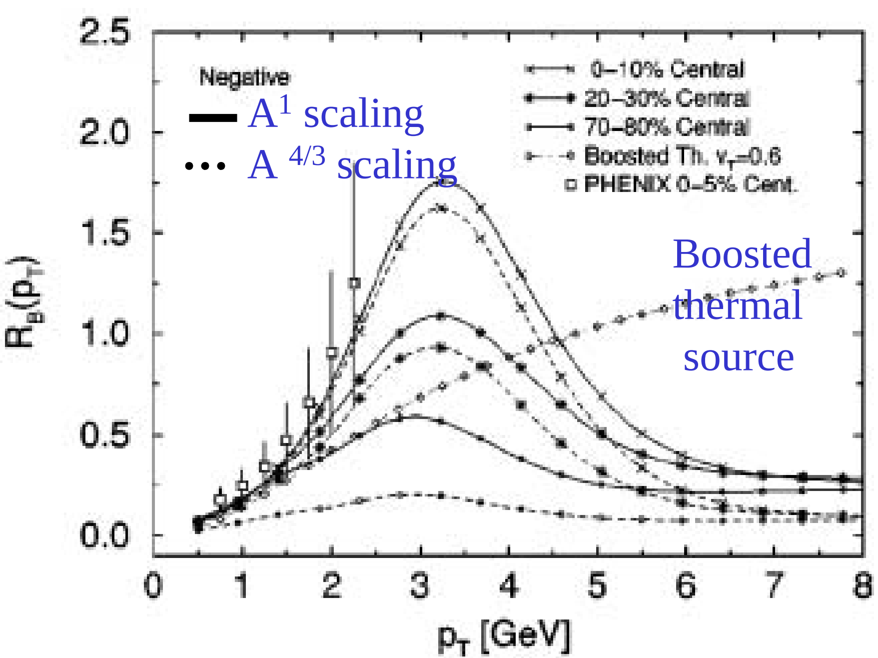


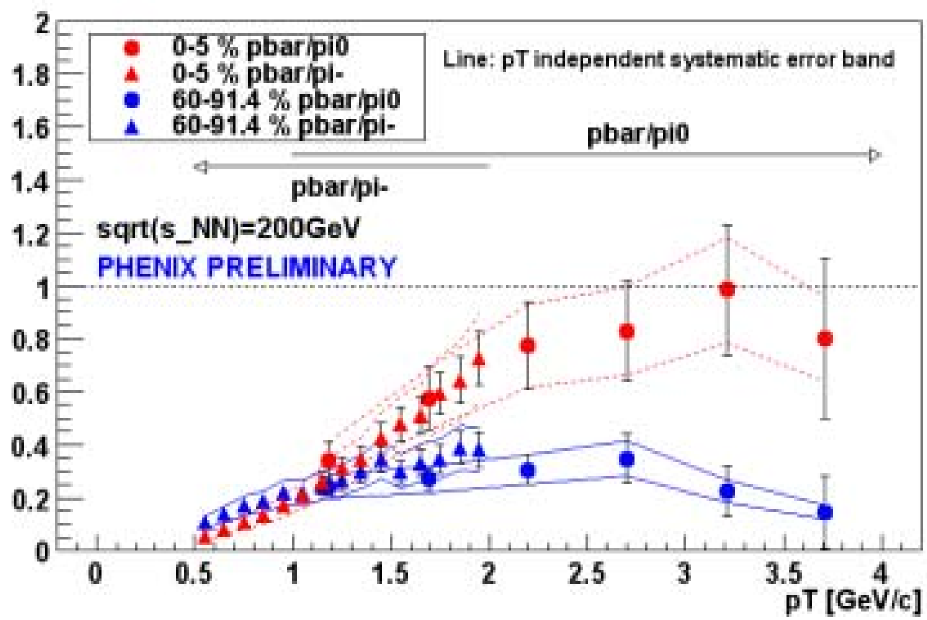
Baryon/meson ratio

- Enhancement of p and pbar by the baryon transport via gluon junctions?



I. Vitev and M. Gyulassy, PRC65(2002)041902





Summary and Prospects

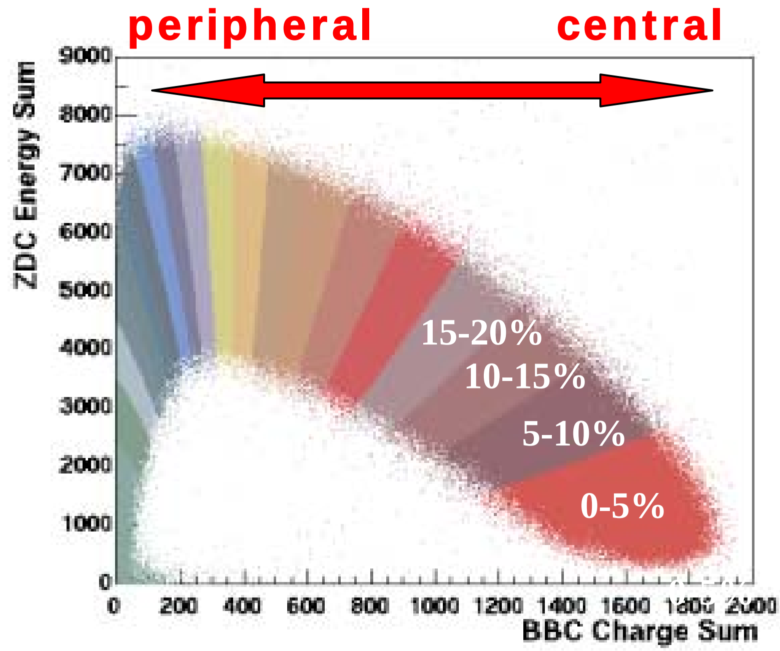
- Initial energy density reached ~5.5GeV/fm^3 at sqrt(S_{NN})=200GeV.
- Naïve mini-jet model (HIJING) was excluded in Nch(200)/Nch(130).
- Hydrodynamic collective expansion well describes the system evolution in p_T < 2GeV, but does not satisfactorily describe the short duration time of freeze-out in HBT and elliptic flow in pt>2GeV.
- Jets were observed well above elliptic flow effect in Au+Au collisions.
- Qualitatively same suppressions of high p_T hadrons were observed both in 130 GeV and 200 GeV.
- Different strength of suppressions were observed. $\pi^0/h^\pm/2$ was ~0.5.
- Enhancement of p and pbar to pion yield in high p_T range was observed.

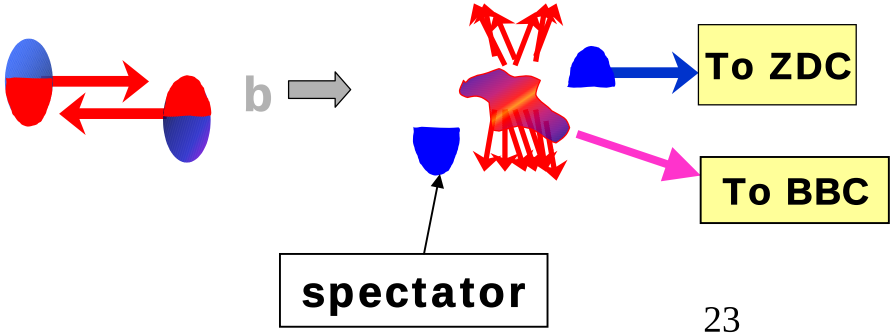
Why protons are not so much suppressed?
What is the source of high p_T protons,
from trivial jet fragments or non trivial collective source?
We need to investigate it in further higher p_T region !!!

Back up slides

Centrality Determination

- **Event characterization in terms of impact parameter (b) in Au+Au collisions.**
  - **Large : peripheral collision**
  - **Small : central collision**
- **Coincidence between BBC and ZDC.**
  - Determine collision centrality.
  - 92 % of inelastic cross section can be seen.
- **Extract variables using Glauber Model**
  - **Number of participants (*N_part*).**
    - Number of nucleons participate in a collision.
    - Represents centrality.
    - Related with soft physics.
  - **Number of binary collisions (*N_binary*).**
    - Number of Nucleon-Nucleon collisions.
    - Related with hard physics.
    - Incoherent sum of N-N collisions becomes a baseline for A-A collisions.





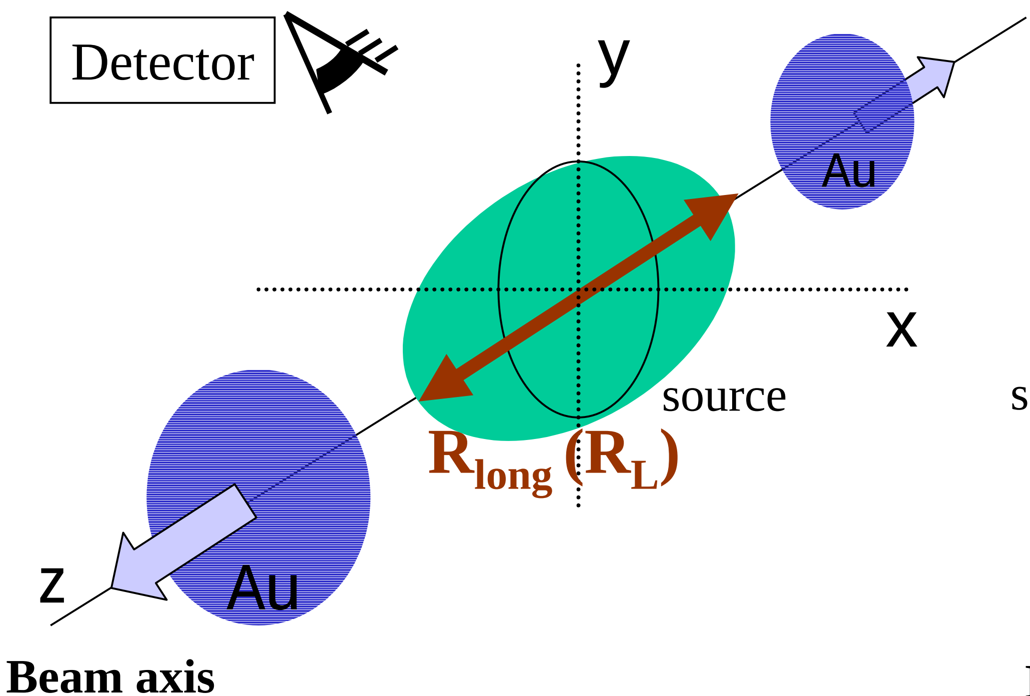
Bertsch-Pratt source radii

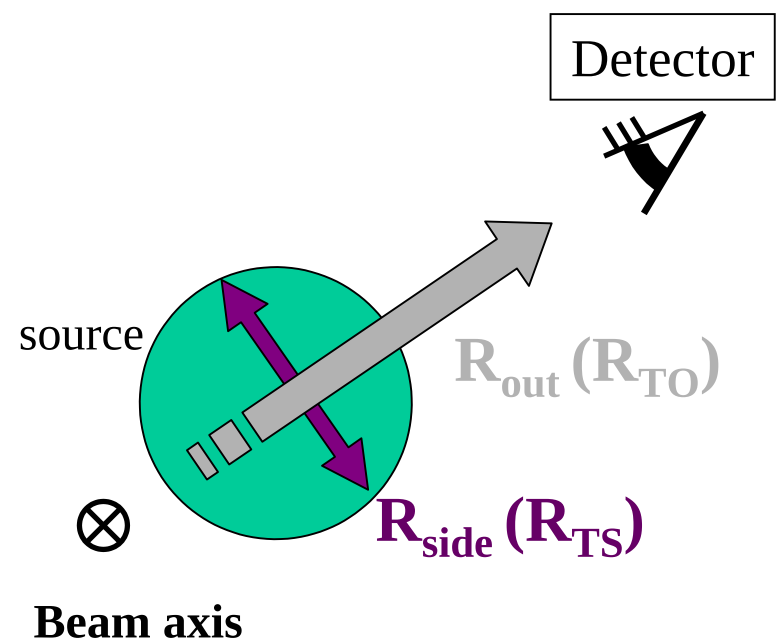
$$C_2 \equiv 1+\lambda \exp\left(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2\right)$$

In LCMS frame

The duration time

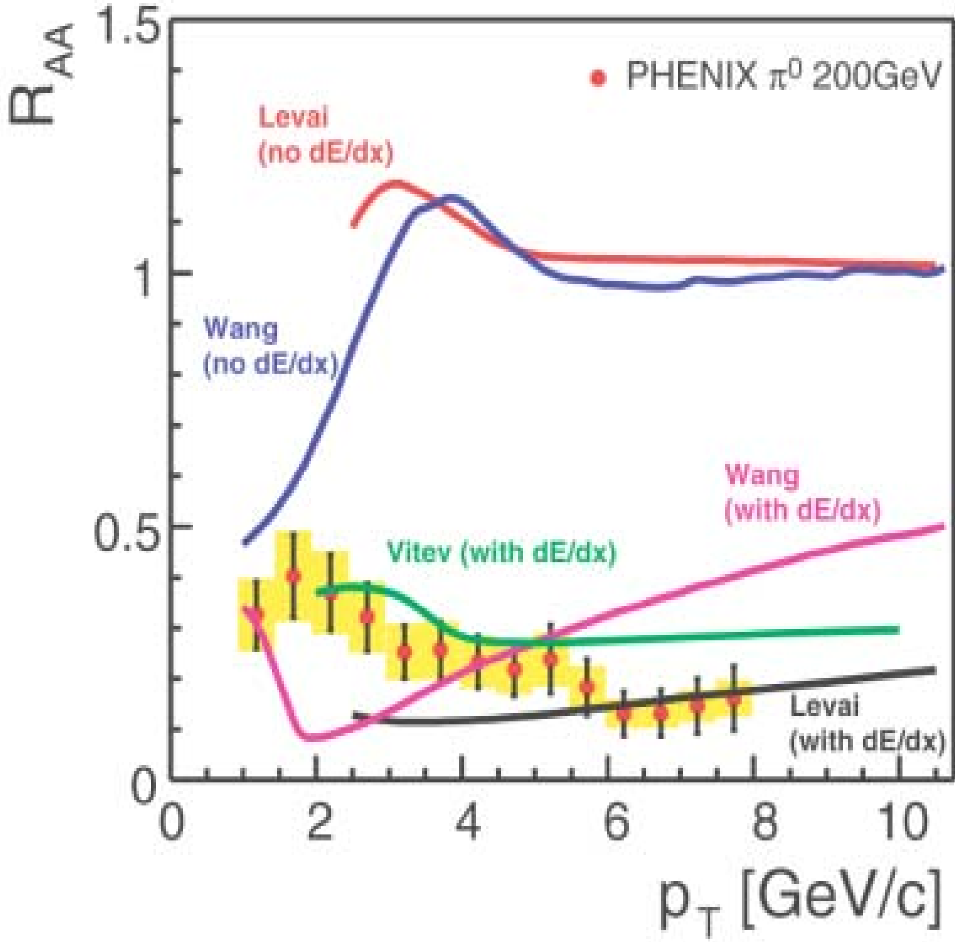
$$\Delta\tau = \sqrt{R_{TO}^2 - R_{TS}^2} / \beta$$





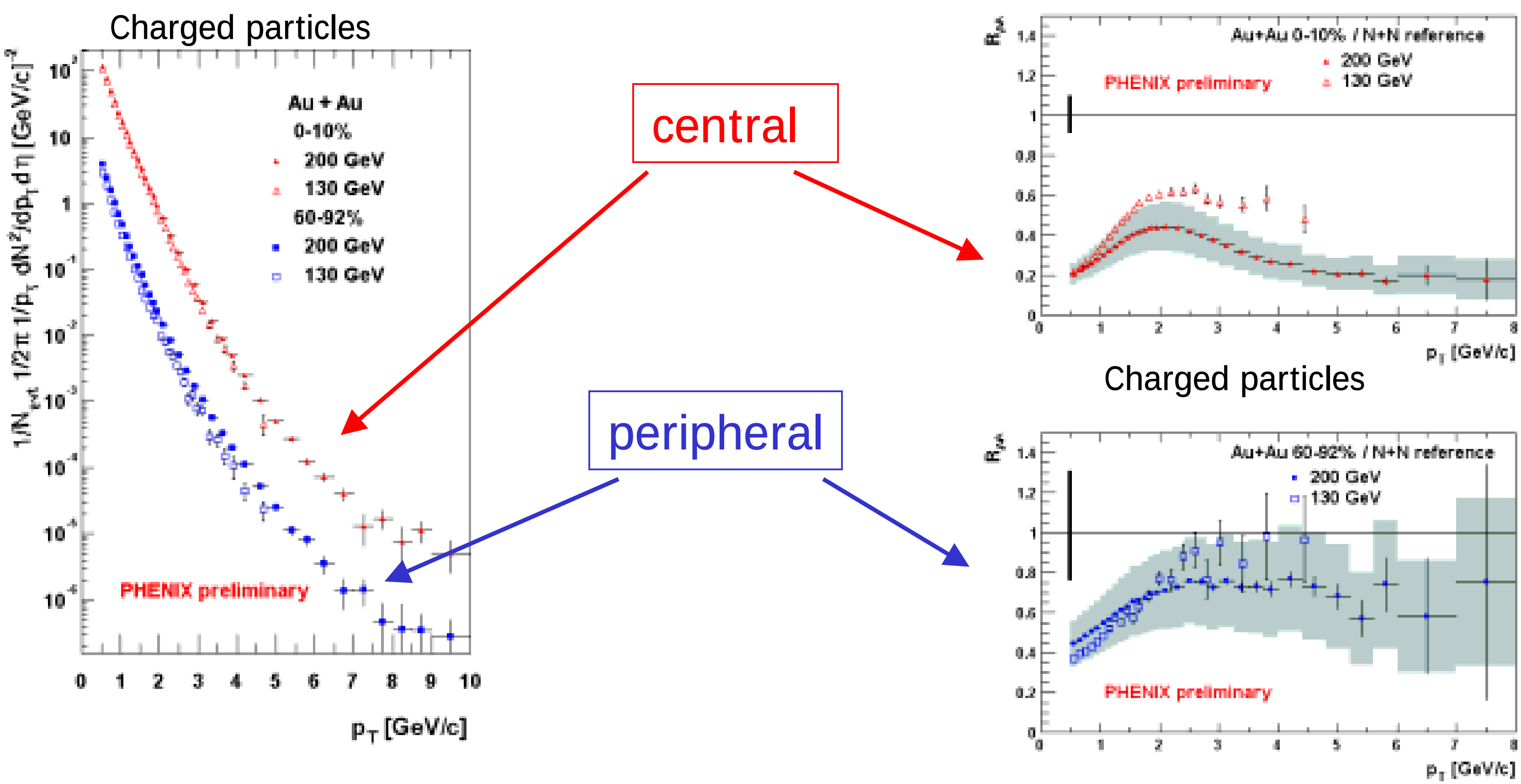
High p_T Neutral Pion Suppression – PHENIX Comparison To Theory

- pQCD calculations:
  - P. Levai, Nucl.Phys.A698 (2002) 63
  - X.N. Wang, Phys.Rev.C61 (200) 06491
  - I. Vitev, talk at QM2002
- so far suppression not described by theories
  - calculations without energy loss completely off
  - energy loss calculations show different p_T dependence



130 vs 200 GeV/c

Higher statistic allow to reach higher transverse momenta.
Qualitatively the same effect is present
Increased magnitude or different particle composition ?



Nuclear Modification Factor

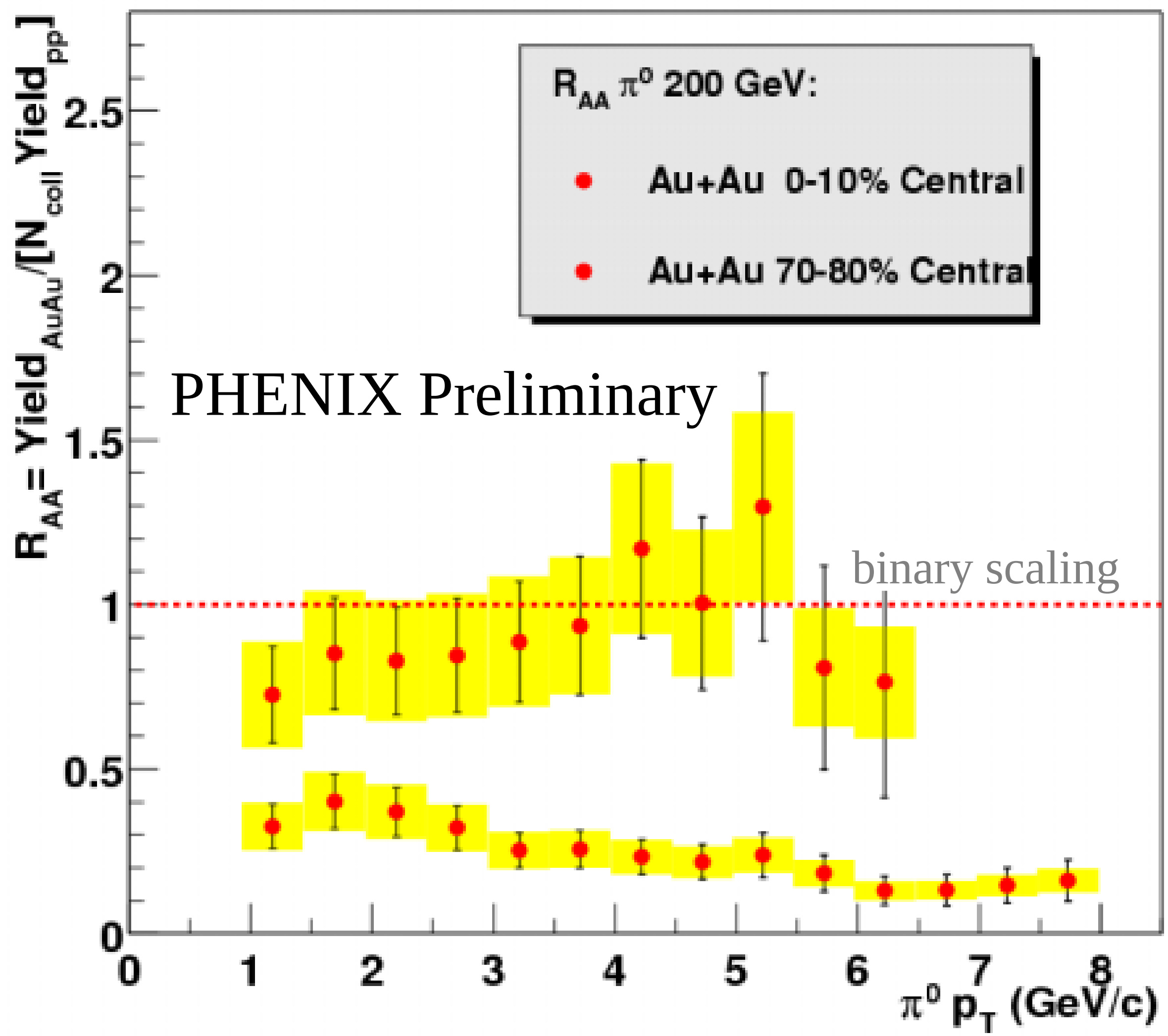
$$R_{AA}(p_T) = \frac{1/N_{events}\, d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle (d^2\sigma_{pp}/dp_T d\eta / \sigma^{pp}_{inelastic})} =$$

$$\frac{Yield_{peripheral} / \langle N_{binary} \rangle_{peripheral}}{Yield_{pp}}$$

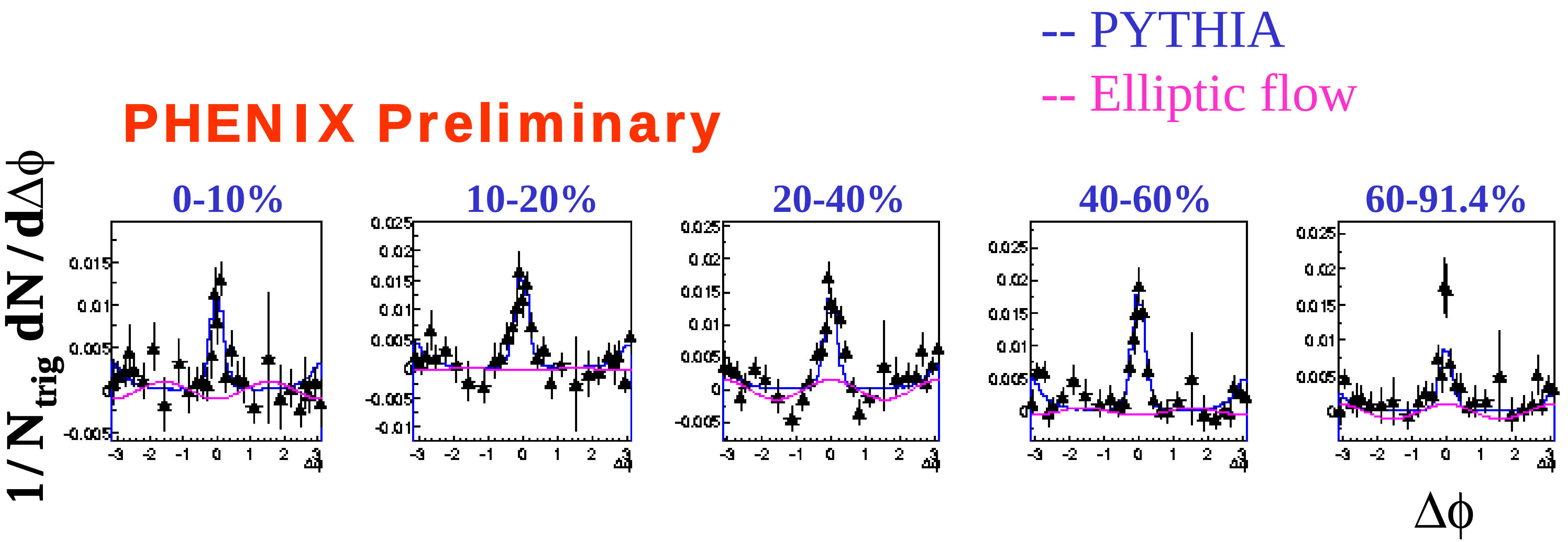
→ Comparison of peripheral to central

RHIC 200 GeV

- central - Suppression
- peripheral – N_{coll} scaling



Evidence for jets in Au+Au



In p_T 2-4 GeV/c, the jet-like picture dominates across all centralities, with little contribution from an elliptic flow component.